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Energy intensity of rainwater harvesting systems: A review

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A B S T R A C T

Rainwater Harvesting Systems (RHS) are increasingly used in buildings to mitigate water shortage and rising prices of centralised water supply. Notwithstanding the benefits of RHS, they may also promote adverse impacts mainly related to the high consumption of energy. In this context, energy intensity (i.e. unit of energy per unit of water) is a crucial parameter for assessing the environmental feasibility of different RHS. However, only recently has attention been drawn to the connection between water and energy consumption, which has been prompted by the increasing importance of water security, energy efficiency and economic feasibility. This connection, known as the water-energy nexus, has been increasingly acknowledged as a key principal for water planning. The objective of this study is twofold: (i) to review the energy intensity data reported for RHS; and (ii) to outline strategies to enhance the energy performance of RHS in buildings. For the reviewed literature, the median energy intensity of theoretical studies (0.20 kWh/m^3) was considerably lower than that described in empirical studies (1.40 kWh/m^3). This implies that theoretical assessments of energy intensity may not sufficiently consider the energy used for pump start-ups and standby mode, as well as the true motor and pump energy efficiency. However, to some extent, this difference may also represent the amount of energy that can be reduced by optimising RHS design and operation. When comparing RHS to conventional town water supply systems, the reviewed empirical studies showed that RHS tend to be three times more energy intensive, although optimised RHS can have more comparable values. Ultimately, it is predominately the local characteristics, such as rainwater demand, building type (single-storey or multi-storey), RHS sub-systems design, potable water plumbing system design, and town water energy intensity, among other factors that will determine whether or not the environmental and economic performances of RHS are acceptable.

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1. Introduction

Cities are intrinsically dependent on water and energy resources just like any living system on Earth. Therefore, the management of both water and energy plays a major role in the development of cities, as well as in the protection of the environment and people's well-being [1]. In this context, the water-energy nexus has been increasingly studied [2–33].

In the last two decades, initiatives to promote water and energy efficiency have been adopted worldwide. Most of these initiatives endeavour to mitigate the impacts of water and energy rising costs [33], enhance water and energy security [34–39], prevent or defer investments in new water and energy public assets [40–43], and reduce pressure on the environment [44,45]. Therefore, water and energy efficiency in buildings are key drivers to achieve social, economic and environmental sustainable development in cities. As such, several water efficiency programs have targeted the use of alternative water sources in buildings. Recent examples of such programs include the Code for Sustainable Homes in the UK [46], the Building Sustainability Index (BASIX) program in New South Wales, Australia [17], and Town Planning Building Regulation in Bologna, Italy [47].

Most of the sustainable building codes mandate or recommend the installation of Rainwater Harvesting Systems (RHS) in buildings to achieve sustainable development objectives. The widespread perception of RHS as an environmentally friendly initiative stem from its benefits for integrated water management strategies, including but not limited to: potable water savings; mitigation of flooding in urban catchments and extensive impervious areas; reduction of nutrient loads to waterways; and increased lifespan of constrained centralised water distribution infrastructure due to demand reductions. Notwithstanding the water management benefits derived from the use of rainwater in buildings, RHS may also have to be energy efficient in order to promote energy and carbon benefits in comparison to conventional water supply systems. Moreover, energy efficient or energy neutral RHS are important to achieve water efficiency where energy supply is limited and thus expensive (e.g. islands and developing countries).

As discussed by Urmme et al. [48], water and energy efficiency initiatives in buildings may be undermined by the paucity of practical advice and information. The sustainable management of the water and energy sectors in a resource limited world depends on the availability of accurate data [49]. Currently, there is a lack of information about the energy intensity of water services [3,50], including information about the energy intensity of RHS [51]. With the increasing application of alternative water sources, in particular rainwater, information about the energy intensity of such alternatives is paramount for designers and planners to ensure the incorporation of water and energy efficiency objectives into the development of sustainable water strategies. Therefore, the objective of this study is twofold: (i) to review the energy intensity data reported for RHS; and (ii) to outline strategies to enhance the energy performance of RHS in buildings.

2. Evolution of water management practices

From the late nineteenth century, urban population growth and public health drivers necessitated better management of water resources in cities, resulting in the introduction of sanitation services through centralised water and wastewater systems [52].

Centralised systems not only ensured sanitary security, but also brought about improved water security, enabling the growth of cities even in areas with limited water availability [53]. To increase the supply of water in cities, the implementation of long-distance water transfer pipelines and the use of large-scale groundwater bores became common practices when energy was plentiful [8]. Traditional urban water planning policy and practices have been focused on recommending large-scale capital intensive supply-side solutions (i.e. dams, desalination, bulk recycled) to meet planned increases in water demand [54].

Despite the benefits of centralised systems (e.g. enhanced public health and water security), they have been shown to be unsustainable in many regions [55]. In recent decades, even with the use of long-distance water transfer schemes and aquifer water, water supply security has declined in several regions worldwide [56,57]. As a result of population growth, water availability will continue to decline in urban areas, especially in developing countries [58,59]. For example, in Brazil, the north-eastern and south-eastern regions, where most of the population is concentrated, may be subjected to periods of considerable water shortages in the coming years [60].

Since the 1990s, water management practices have been evolving [56]. Rygaard et al. [53] claimed that once again, urban population growth has stimulated the commencement of a new era for water management, which will enable cities to be water self-sufficient. Gleick [61] states that there hasbeen a major transition from a “hard path”, where water management is focused exclusively on meeting the increasing water demand, to a “soft path”, in which centralised water systems are complemented by lower cost community-scale systems. He also promotes a carefully planned portfolio of traditional and contemporary centralised and decentralised supply schemes in order to meet community ecological, financial and societal objectives [61].

To ensure the sustainability of the water sector, new policies for integrated water management are emerging [62,63]. The demand-side principles incorporated into such policies encompass financial measures (incentives, tariff adjustment), non-financial measures (awareness campaigns, promotion of technologies for water efficiency), mandatory measures (water regulations) or optional measures (water certifications) [64–66]. For Lundin and Morrison [67], the sustainability of public water services depends on the adoption of technologies that save water, increase energy efficiency and enable the recycling of water and nutrients.

According to Rygaard et al. [53], for determining strategies and technologies for water self-sufficiency, it is necessary to define the boundaries of the studied area, such as: watershed, city or

building. Therefore, it implies the switch from centralised water and wastewater systems to decentralised systems either on a building or community scale. Turner and White [68] state that the development of integrated water management schemes encompasses the calculation of the water supply and demand balance, determination of initiatives to control this balance, implementation and monitoring of initiatives, and evaluation and review of the scheme performance. In this new complex era of integrated urban water planning and management, significant changes in planning, constructing, managing, and assessing the performance of water assets will be necessary.

3. Rainwater harvesting systems in buildings

As a major component of water consumption in cities, buildings have been targeted by recent water management policies in order to promote water savings on an urban scale. As a result, the water consumption patterns per capita have decreased in several cities and countries; for example, in Australia [69], the USA [70] and the UK [71].

Enhanced water management in buildings is primarily achieved through two overarching strategies [53,67,72–74]: demand-side management and supply-side management. Demand-side water management involves the conservation of water resources. This principal is usually adopted in buildings through the use of water efficient appliances and fixtures [40,75,76]. Likewise, awareness campaigns [77] and visual display technologies to inform users about their water consumption patterns [78] are also approaches employed to promote water conservation, as water demand reduction also depends on a change in the water use behaviour of consumers [46,79,80]. Conversely, supply-side water management strategies have focused on diversifying water supply options by encouraging the use of alternative water sources in buildings (i.e. potable source substitution with recycled or rainwater).

Among the numerous on-site alternative water supply sources available, the use of RHS is the most prevalent, as it is often considered as a lower cost and less risky option for public health [41,59,60,73,74,81–94]. RHS configuration can vary significantly depending on the building characteristics (e.g. roof area), rainfall reliability, level of consumer demand, and the water quality level required forend uses supplied by rainwater (e.g. toilet requires lower quality water than kitchen tap). RHS are divided into five major sub-systems, including: (i) collection system; (ii) treatment system; (iii) storage system; (iv) distribution system; and (v) water back-up system. Table 1 presents the main features of each sub-system. The configuration of each rainwater harvesting sub-system will vary depending on local practices and components availability. Table 2 shows the features of typical sub-system configurations for RHS worldwide.

In urban areas, RHS are typically used to supply water to non-potable end uses, although there are also potable applications of rainwater. The commonly utilised distribution system design varies among regions. For instance, in Australia, rainwater is usually pumped from storage tanks to end use points (i.e. direct supply) [17]; whereas, in Brazil, rainwater is generally pumped to header tanks, and then distributed by gravity (i.e. indirect supply) [60].

4. Energy efficiency in the water sector

In general, Life Cycle Assessment (LCA) studies indicate that most of the environmental burdens of water and wastewater services derive from energy consumption during their operational phase [24,95–103], in which the systems perform their intended function (i.e. provision of water or wastewater services). To assess the comparative energetics of different water systems, the indicator energy intensity (kWh/m^3) is being increasingly applied as a latent variable of environmental performance [95,104,105].

As a result of water quality deterioration and/or water shortageto meet the increasing water demand in urban areas, the energy consumption of the water sector is likely to expand. This issue may be further exacerbated with population growth and climate change [106]. Ultimately, it may lead to the use of raw water sources with poor quality or from distant locations. In this context, more energy will be required to treat and/or transport water [2,107], as the greater the difference between raw and treated water quality, or the longer the distance from water source and consumption points, the more energy to supply water is required. Moreover, the energy intensity may also increase with the implementation of more restrictive regulatory requirements for water quality [108,109].

The consequences of water scarcity are likely to be even more severe in developing countries due to their more constrained and intermittent supply of electricity. This, in turn, will limit their capacity to develop mitigation strategies for water scarcity through new energy intensive technologies (e.g. recycled water, desalination and long-distance water transfer), as has been the case in advanced economies. Therefore, in developing countries, energy efficient or energy neutral water supply technologies will play an important whole for water security. In developed countries, regardless the ability to secure the energy to underpin ever-increasing water supply demands, environmentally concerned constituencies will enforce the efficient use of energy.

The feasibility of water supply systems tends to increase with a decrease in their energy intensity, as a result of a reduction in whole-of-life operational costs. Therefore, energy intensity indicators are becoming increasingly important in the suite of evaluation parameters for benchmarking and comparing any new or retrofitted water supply solutions.

Theoretically, rainwater should require the least amount of energy among the major alternative water sources (e.g. salt water, recycled water, grey water) for water supply in urban areas, due to its typical high water quality in relation to other alternative water

Table 1
Rainwater harvesting sub-systems.

Sub-system	Function	Main parts and components	Design criteria
Collection	Collect and convey rainwater	Catchment area, and conveyance pipes (gutters and downpipes)	Optimisation of the quality and quantity of raw rainwater yields
Treatment	Improve rainwater quality	Treatment equipment or apparatus	Quality control to comply with guidelines for non-potable and seldom potable water use
Storage	Reserve rainwater for future use	Storage tank	Balance between rainwater yield and consumption
Distribution	Supply rainwater from storage tank to end use points	Distribution apparatus (e.g. pipes, connections, pumps, header tanks)	Required supply pressure and flow rate, installation and operation costs, and energy consumption
Town water back-up	Supplement rainwater supply when rainwater cannot meet demand	Rainwater back-up apparatus (e.g. valves and controllers) to enable switching to town water supply	Ensure continuous reliable supply of water to consumption points when rainwater is not available

Table 2
Common types of rainwater harvesting sub-systems.

Sub-system	Common practices	Type/applicability	Description
Collection	Roof catchment	All types	Determination of the catchment area as the roof area
Treatment	First flush diversion	All types	Diversion of the initial runoff from catchment areas in chambers installed in conjunction with, or subsequent to, downpipes to avoid the ingress of excessive concentrations of suspended solids, pathogens and organic matter in storage tanks
	Gross filtration	All types	Installation of strainers to avoid the ingress of gross pollutants in storage tanks
	Fine filtration	All types	Installation of filters to eliminate small particles that may be associated with pathogens
	UV disinfection	Compliance with higher water quality requirements (e.g. Potable water)	Disinfection with ultraviolet (UV) radiation to eliminate pathogens
	Chemical disinfection	Compliance with higher water quality requirements (e.g. Potable water)	Disinfection with chemicals (e.g. chlorination) to eliminate pathogens
Storage	Large tanks	All types	Installation of tanks with large dimensions (i.e. usually round shaped tanks) at ground or sub-ground levels
	Slim line tanks	All types	Installation of slim line tanks at ground level with low footprint (i.e. less than 1 m wide) and storage capacity over 3.000 L
Distribution	Direct external supply	Fixed speed pump	Direct feed to external end uses using fixed speed pumps for irrigation and other external end uses supply
	Direct internal and external supply	Fixed speed pump	Direct feed to internal and external uses using fixed speed pumps for irrigation, toilet flushing, laundry, and other external end use supply
		Variable speed pump	Direct feed to internal and external uses using variable speed pumps for irrigation, toilet flushing, laundry, and other external end use supply
		Pressure vessel	Direct feed from pressure vessel to internal and external uses using fixed or variable speed pumps for irrigation, toilet flushing, laundry, and other external end uses supply
	Header tank	Indirect supply	Pumping from storage tank to header tank using fixed speed pump, and gravity distribution from header tank to required end use points
		Direct supply	Direct gravity conveyance of rainwater from collection system to suspended storage tank (header tank), and gravity distribution from header tank to supplied end use points
Town water back-up	Trickle top-up	All types	Supply town water to either rainwater storage tank or header tank when levels drop below minimum threshold
	Automatic switch	All types	Supply town water to end use points when rainwater is not available using level sensors in the rainwater tank and solenoid valves

sources. Rainwater use usually involves none or primary treatment methods to meet water quality guidelines for non-potable end uses (i.e. typical intended end use of rainwater) [110]; whereas other alternative water sources may require more advanced treatment methods (e.g. membrane filtration) [53,110–112], which generally demand more energy. On the other hand, RHS may have a lower energy performance in relation to centralised systems depending on site specific conditions, system configuration and economies of scale.

5. Energy intensity of rainwater systems

5.1. Critique of reported theoretical studies

The energy intensity of theoretical studies was calculated considering different assumptions and configurations of RHS, which is summarised in Table 3.

Chiu et al. [113] estimated energy savings by using RHS in single-family one-storey housesin a hilly area of Taipei, Taiwan. The theoretically calculated energy intensity was determined as 0.06 kWh/m³ for RHS and was compared to the 3.25 kWh/m³ value calculated for the centralised town water supply system in the studied area. The RHS was composed of two rainwater tanks; one larger at ground level for rainwater collection, and another at roof level for rainwater distribution via a header tank to the end use points. The transfer of water from the ground level tank to the header tank was assumed to be performed daily by an ideally-sized pump with 393 W power rating and optimal flow rate of 60 m³/h with pump and motor efficiencies of 65% and 100%, respectively. Chiu et al. [113] potentially underestimated the energy intensity of low power pumps since they did not consider standby and start-up energy consumption and also presented optimistic assumptions about motor and pump efficiencies. Nonetheless, this study is still of value since it provides clues that very low values of energy intensity can be achieved when using header tanks and optimised pump sizing and scheduling.

The energy intensity of the pumping system (0.06 kWh/m³) in the study of Chiu et al. [113] was calculated in accordance with the equations described in Cheng [114], which are similar to basic theoretical pump power (Eq. (1)) and pump energy intensity (Eq. (2)) equations, also described in other studies [3,17,115].

$$P_{MB} \geq \frac{\rho\, g\, H\, Q}{\eta_M \eta_p} \tag{1}$$

where P_{MB} is the pump input power (W), ρ is the liquid density (kg/m³), g is the gravitational acceleration (m/s²), H is the total head (i.e. geometrical height and friction loss height) (m), Q is the flow rate (m³/s), η_M is the motor efficiency (dimensionless), and η_p is the pump efficiency (dimensionless). Note that 1 J is equal to 1 W s and 1 kg m²/s².

$$EI_{MP} = \frac{P_{MB}}{Q} \tag{2}$$

where, EI_{MP} is the energy intensity of the pumping system (kWh/m³), P_{MB} is the pump input power (kW), and Q is the flow rate (m³/h).

Usually, calculation methods similar to Eqs. (1) and (2) are used to determine the energy intensity for the operational phase of pumping systems taking into account the optimal motor pump efficiency described by manufacturers. Such motor pump efficiency is represented in Eq. (1) by the motor efficiency and the pump efficiency, and can only be achieved when the pump motor operates at the best efficiency point of optimal flow rate and head.

Table 3
RHS configuration for reviewed theoretical studies.

References			[113]	[116]	[118]	[117]	[115]	[101]	[101]	[101]	[119]
Location	*Country*	*City*									
	Taiwan	Taipei	✓								
	Australia	*None specified*		✓							
		Melbourne			✓						
	Brazil	Florianópolis				✓	✓				
	Spain	Barcelona						✓	✓	✓	
	UK	Exeter									✓
Building type	Single-storey detached residential		✓	✓	✓	✓	✓				
	Multi-storey residential							✓	✓	✓	
	Multi-storey commercial										✓
Rainwater end uses	Toilet flushing		✓	✓	✓	✓	✓				✓
	Laundry			✓		✓	✓	✓	✓	✓	
	Irrigation		✓		✓						
Rainwater harvesting sub-system	Collection	Roof	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Treatment	First flush diversion					✓				
		Filtration									✓
		UV disinfection					✓				
	Storage	H tank at building						✓			
		GL tank at building	✓	✓	✓	✓	✓				
		UG tank at building							✓		✓
		UG tank at block								✓	
	Distribution	H tank	✓	✓		✓	✓	✓			✓
		Pumping			✓				✓	✓	
	Town water back-up	To H tank				✓	✓				
		To GL tank									
Energy demand	Active pumping	GL tank to H tank	✓	✓		✓	✓				
		GL tank to end uses			✓						
		UG tank to H tank									✓
		UG tank to end uses							✓	✓	
	Pump standby power						✓				✓
	Pump start-up power						✓				✓
	Pump power rating (W) – range		393	250	600	186	416	0	250, 2200	500, 4400	1100
	Pumping	Median	0.06	0.04	0.30	0.18	0.20	0.00	2.35	1.54	0.54
	energy	Average	0.06	0.04	0.30	0.18	0.26	0.00	2.35	1.54	0.54
	intensity	Min	–	–	0.24	–	0.14	–	–	0.97	–
	(kWh/m^3)	Max	–	–	0.36	–	0.57	–	–	2.10	–

Note: ground level (GL), underground (UG) and header (H).

While fixed speed pumps have one best efficiency point, variable speed pumps have several best efficiency points as they adjust the pump rotation to the used flow rate. However, variable speed pumps are usually considerably more expensive than fixed speed pumps, and hence are not largely applied in RHS. It is important to note that the pump motor efficiency must be accounted for in the calculation of the energy intensity in Eq. (2) when the pump motor power rating is used in place of the pump input power. If the pump power calculated through Eq. (1) is used to calculate the energy intensity through Eq. (2), the motor pump efficiency is already considered.

In Australia, Cunio and Sproul [116] carried out estimations for different configurations of RHS pumping systems through theoretical and empirical analysis. The theoretical component of the study was comprised of an estimation of the energy intensity of optimised rainwater pumping systems with header tanks at a height of 4 m (i.e. low pressure distribution system). The calculated energy intensity for such system was equal to 0.04 kWh/m^3. Similar to Chiu et al. [113], Cunio and Sproul [116] considered pump operation only to supply rainwater from a ground level tank to a header tank through a 50 mm polyethylene pipe by using a 250 W centrifugal pump, and then gravity rainwater distribution from the header tank to low flow and low pressure rainwater end uses. In this study, the use of pipes with large internal diameter was considered in order to reduce friction losses during rainwater pumping from the ground level tank to the header tank, which in turn reduces required pump pressure head and associated energy consumption. In order to maintain low head losses, the authors also emphasised the importance of using header tanks float valves with high flow and low resistance specification to permit the rapid switch from open to close status when the maximum capacity of the header tank is reached. Cunio and Sproul [116] estimated energy savings in RHS equal to 85% by using header tanks in RHS in relation to the energy intensity of the centralised water supply system in Sydney in 2003 (i.e. 0.26 kWh/m^3). However, pump standby and start-up power consumption were not taken into account, which possibly led to an underestimation of the energy intensity of RHS. Among the benefits of RHS with header tank distribution, Cunio and Sproul [116] indicate the reduction of operational energy consumption while maintaining similar installation costs compared with standard high pressure rainwater distribution systems (i.e. direct supply systems). Only minor limitations were observed relating to the prolonged time to fill cisterns at flow rates of approximately 0.09 L/h.

In Brazil, Ghisi and Oliveira [117] calculated the theoretical consumption of energy for RHS in two one-storey residential buildings in Florianópolis. The authors considered similar assumptions as Chiu et al. [113], in which the pump operation was performed daily to lift rainwater from a ground level rainwater tank to a header tank for the supply of toilets and laundry. In the study, it was assumed that a 1/4 HP (186 W) pump with a flow rate of 2.7 m^3/h and an electrical consumption of 0.5 kWh was used. Therefore, the motor pump efficiency was approximately 37%. Considering the energy consumption and the pump flow rate

described in the study, the energy intensity of the system, calculated using Eq. (2), was estimated as 0.18 kWh/m^3.

In 2003, Yarra Valley Water, the water utility servicing the northern and eastern suburbs of Melbourne, Australia, undertook a study to determine the environmental performance of on-site RHS in comparison to centralised town water supply systems [118]. Two scenarios with rainwater use were studied: (i) installation of 600 L rainwater tank for garden irrigation use only without the use of pumping; and (ii) installation of 2250 L rainwater tank for garden and toilet flushing with the use of a pumping system. For the scenario with pumping, the energy intensity was calculated using a similar method than the one described in Eq. (2), in which it was assumed that a 600 W pump and flow rates between 1.7 and 2.5 m^3/h were used for toilet flushing and irrigation, respectively. The estimated energy intensity was equal to 0.24 kWh/m^3 for irrigation and 0.36 kWh/m^3 for toilet flushing.

Vieira [115] estimated the energy intensity of RHS in low-income households in Florianópolis, Brazil. Similarly to Ghisi and Oliveira [117], the author considered the use of rainwater for toilet and laundry supply only, because there was minimal irrigation demand in the studied households. The RHS was designed to achieve maximum energy efficiency in single-storey detached houses. Thus, the rainwater plumbing distribution system was designed using header tanks with one pump operation per day in order to avoid multiple start-ups of pumps, as start-ups can be more energy intensive than constant flow operation [17,119]. Moreover, so as to guarantee a more efficient pumping operation, it was assumed that a 416 W pump with 7.89 m^3/h flow rate and respective pump and motor efficiencies of 62% and 48% was used. This was the most efficient pump motor under 1 kW power among 15 motor pumps available in the PROCEL (Brazilian Program of Energy Efficiency) catalogue.

In the study of Vieira [115], the energy intensity was calculated using Eq. (3), which is more comprehensive than Eq. (2) as it considers not only the operational energy intensity, but also the energy required for standby mode and pump start-up.

$$IE_{MP} = \left[\frac{P_{MP}}{Q}\right] + \left[\frac{(C_{su}N_{su}) + (P_{sb}t_{sb})}{V}\right] \quad (3)$$

where IE_{MP} is the energy intensity of the pumping systems (kWh/m^3), P_{MP} is the pump inputpower (kW), Q is the flow rate (m^3/h), C_{su} is the energy consumption for pump start-up (kWh/start-up), N_{su} is the number of start-up operations (start-up/day), P_{sb} is the power rate for standby mode (kW), t_{sb} is the period the system operates in standby mode (hours/day), and V is the rainwater consumption (m^3/day).

Vieira [115] considered the energy consumption for pump start-up equal to 30 s of constant flow operation and the power rate for standby mode equal to 2 W, as similarly described in Retamal et al. [17]. The energy intensity calculated for the pumping system ranged between 0.14 and 0.57 kWh/m^3 for RHS with daily rainwater demand equal to 600 and 100 L/day, respectively. Out of this total, 0.05 kWh/m^3 was associated with active pumping, 0.01 to 0.03 kWh/m^3 with pump start-ups, and 0.08 to 0.48 kWh/m^3 with standby power. The results show that the lower the rainwater demand, the higher the energy intensity. This inverse correlation is related to the energy consumed for standby mode and pump start-ups, which consume approximately the same amount of energy regardless the water consumption volume. Therefore, there is an economies of scale if more rainwater is consumed, as the amount of energy per volume of water will decrease, reducing the energy intensity of RHS.

In a study carried out in the UK, Ward et al. [119] developed a method to estimate the energy consumption of pumping systems in RHS. Such a method can also be used to calculate the energy intensity of rainwater pumping systems by determining the relation between the total energy consumption and the total rainwater consumption in a period of time. Similarly to Vieira [115], the pump efficiency and the energy related to pump start-ups were also taken into account, which is presented in a concise way in Eq. (4) [119].

$$E_{TOT} = \left\{\left[P_R \times \left(\frac{V_1}{P_C}\right)\right] + \left[\left(P_R \times \frac{V_2}{P_c}\right) \times (1+S_F)\right]\right\} \times \left\{1 + \left(1 - \frac{P_R}{P_I}\right)\right\} \quad (4)$$

where E_{TOT} is the total energy consumed in the pumping system (kWh), V_1 is the volume pumped during constant flow operation (m^3), V_2 is the volume pumped during start-up (m^3), S_F is the start-up energy factor (extra energy used during start-up in relation to constant flow operation) (dimensionless), P_R is the motor pump power rating (kW), P_I is the motor input power (kW), and P_c is the pump capacity (flow rate) (m^3/h).

In order to calculate the pump efficiency, Ward et al. [119] considered the motor pump power rating and the input power provided by manufacturers. The energy for start-ups was estimated by considering the extra energy used for start-up expressed by a start-up energy factor, and the volume pumped during start-ups. This last parameter was calculated using the percentage of pumped water during start-ups, the rainwater tank volume, and the level in which the float switch is set to turn-on and turn-off the pump. By using such a method, it was estimated that the average energy intensity calculated for RHS at a particular office building in Exeter in the UK would increase from 0.32 kWh/m^3 (using a simplified method) to 0.54 kWh/m^3. The simplified method is similar to Eq. (2), in which the energy consumption for pump start-ups is not considered. The energy intensity calculated by the more comprehensive method is 69% greater than that calculated for the more simplified equation [119].

Also in the UK, the Market Transformation Programme developed by the Department for Environment Food and Rural Affairs (DEFRA) [120] estimated an energy intensity of approximately 0.60 kWh/m^3 for RHS. In Belgium, Campling et al. [121] described local guidelines which also consider an energy intensity of 0.60 kWh/m^3 for new RHS. In such a system, energy is used only for pumping rainwater from an underground tank to consumption points. In Denmark, Mikkelsen et al. [122] found that the energy intensity of RHS with direct feed through pumping from the underground rainwater tank to end use points varied around 0.30 and 0.50 kWh/m^3.

Angrill et al. [101] developed a LCA model to analyse the environmental performance of RHS for Mediterranean urban areas. Eight scenarios for the installation of RHS in new building developments were studied by considering the combination of two multi-family building types and four rainwater tank locations, including: (i) buildings with two-storey in diffuse (low density urban) areas, and buildings with five-storey in compact (high density urban) areas; and (ii) rainwater storage at a block scale in underground tanks, and at a building scale in underground, below roof and distributed over roof tanks. Rainwater use was considered exclusively for laundry purposes. The conclusions of this study indicate that RHS with direct collection and distribution of rainwater in header tanks presented the best environmental performance as they do not require pumping. The energy intensity of scenarios in which pumping was considered to distribute rainwater was equal to 0.49 and 0.97 kWh/m^3 in buildings within low density urban areas with underground rainwater tanks at building and block scales, respectively. Within high density urban areas with underground tanks at building and block scales, this parameter increased to 2.1 and 4.2 kWh/m^3, respectively. The method used by Angrill et al. [101]

to calculate the energy intensity of pumping systems was not detailed in their article. In accordance to the authors, the energy efficiency and environmental performance of RHS can be optimised by carefully considering the intended rainwater end uses and available technologies, as well as economic, environmental and social factors.

Most of the reviewed theoretical studies described low energy intensity values for rainwater pumping systems, which indicate that theoretically a small amount of energy is required to pump rainwater. Nonetheless, not only do rainwater pumping systems demand energy to pump water, but they also require energy during standby mode and pump start-ups. The majority of the reviewed theoretical studies did not consider standby and start-up energy consumption, and hence their reported low energy intensity values are likely to be underestimated.

Despite the limitations of theoretical studies, they provided important clues to improve the energy efficiency of RHS, including: (i) the use of header tanks to enhance the performance of pumping systems by reducing the number of pump start-ups and adjusting the flow rate to the best efficiency point [115,116,119]; (ii) the use of low pressure pumps to reduce the total energy embodied into rainwater [116]; (iii) the use of larger pipe diameters to reduce friction losses [116]; (iv) the use of direct supply of rainwater with storage of rainwater in header tanks and distribution by gravity without pumping [101]; (v) the increase of rainwater demand to reduce the energy intensity associated with standby mode and pump start-ups [115].

5.2. Critique of reported empirical studies

The energy intensity of empirical studies was calculated for a range of assumptions and configurations of RHS. A summary of the configuration of RHS described in the reviewed empirical studies is provided in Table 4.

In Australia, Cunio and Sproul [116] carried out estimations for different configurations of RHS pumping systems through empirical and theoretical analysis. The empirical component of the study was comprised of an estimation of the energy intensities of a conventional and an optimised rainwater pumping system. In accordance to Cunio and Sproul [116], most of the internal rainwater residential end uses (e.g. toilet cisterns and laundry) required low flow rates (i.e. < 10 L/min) and pressure (i.e. 1.5 m), and hence can be supplied by low power pumps (e.g. 20 W). Moreover, energy can be saved by reducing friction losses in internally plumbed rainwater systems with the installation of larger pipe diameters (≥ 25 mm) and valves with low friction loss [116]. The experiment carried out by Cunio and Sproul [116] with different rainwater pumping configurations from a ground level tank to a toilet cistern showed a considerable variation of energy consumption. For the conventional rainwater distribution system

Table 4
RHS configuration for reviewed empirical studies.

References			[116]	[116]	[123]	[124]	[125]	[126]	[17]	[128]	[129]	[131]
Location	***Country***	***City***										
	Australia	*None specified*	✓	✓						✓		
		Gold Coast			✓	✓	✓					
		Brisbane									✓	
		Sydney						✓	✓			
	Brazil	Salvador										✓
Experiment type	Laboratory		✓	✓	✓					✓		
	Field					✓	✓	✓	✓		✓	✓
Building type	Single-storey detached residential		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Multi-storey											
Rainwater end uses	Toilet flushing		✓	✓	✓	✓	✓	✓	✓	✓	✓	
	Laundry				✓	✓	✓	✓	✓	✓	✓	✓
	Irrigation				✓	✓	✓	✓	✓	✓	✓	
	Dish washer									✓	✓	
	Taps									✓	✓	
	Shower										✓	
Rainwater harvesting sub-system	Collection	Roof	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Treatment	First flush diversion						✓			✓	
		Fine filtration						✓				
		UV disinfection							✓		✓	
	Storage	H tank at building										✓
		GL tank at building	✓	✓	✓	✓	✓	✓	✓	✓	✓	
		GL tank at block									✓	
	Distribution	H tank (gravity)										✓
		Direct supply (pump)	✓	✓	✓	✓	✓	✓	✓	✓	✓	
	Town water back-up	Manual							✓			
		Automatic Switch			✓		✓	✓	✓			
		Trickle top-up to GL tank					✓	✓	✓		✓	
Energy demand	Active pumping		✓	✓	✓	✓	✓	✓	✓	✓	✓	
	Pump standby power					✓	✓	✓	✓		✓	
	Pump start-up power		✓	✓	✓	✓	✓	✓	✓	✓	✓	
	Pump power rating (W)		18	450	890	700	350	–	500	200	600	0
			22	–	–	–	890	–	890	750	–	0
	Pumping energy intensity (kWh/m³)	Median	0.12	1.70	1.09	1.40	–	1.48	2.00	1.40	2.10	0.00
		Average	0.13	1.70	1.08	–	1.52	2.08	2.35	2.00	2.60	0.00
		Min	0.07	–	1.04	–	1.46	0.76	0.90	0.60	2.00	–
		Max	0.20	–	1.67	–	1.59	10.8	4.90	5.30	3.90	–

Note: ground level (GL), underground (UG) and header (H).

with a 450 W pump and 13 and 19 mm pipes, the energy intensity was equal to 1.70 kWh/m^3 to supply a single flush event of a toilet cistern; whereas, the energy intensity of the low pressure distribution system with 22 W pump and 40 mm pipe for the same toilet cistern was 0.18 kWh/m^3. The performance of the low pressure distribution system was further optimised by replacing the existing cistern float valve (i.e. low flow silent model with minimal operation pressure head of 2 m) by a standard toilet cistern float valve and a low friction loss float valve (i.e. low pressure rural trough float valve). The energy intensity results of the system with the standard toilet cistern float valve and 22 and 18 W pumps ranged from 0.15 to 0.20 kWh/m^3, respectively. More significant energy savings were achieved by using the low friction loss float valve, in which the energy intensity of toilet cistern flushing events were equal to 0.07 and 0.10 kWh/m^3 for 18 and 22 W pumps, respectively.

Talebpour et al. [123] experimentally evaluated the energy intensity of five households located in Gold Coast city, Queensland, Australia. The study applied high resolution smart water (0.014 L/pulse every 5 s) and energy (0.10 Wh every 5 s) metering technology so that the energy intensity of each end use event could be determined. The evaluation focused on conventional rainwater pumping systems installed in Australia that have a direct supply by a fixed speed pump with automatic town water switch (i.e. Davey Rainbank KBR2 with 890 W pump). As per the local building development code requirements at the time, all rainwater tanks had to be internally plumbed into the washing machine and toilet, as well as to supply outdoor end uses [91]. The lowest energy intensity was 1.04 kWh/m^3 for irrigation; whereas the highest was 1.67 kWh/m^3 for half load toilet flushing [123]. The energy intensity varied among different end uses mainly due to the flow rate of events, as, in fixed speed pumps, the highest energy efficiency is reached at a single best efficiencypoint only. Then, when the flow rate of end uses was near to the best efficiency point flow rate, the energy intensity was reduced. For instance, toilet cisterns demonstrated high energy intensity and low flow rates to refill (maximum around 8 L/min), whilst irrigation displayed low energy intensity and high flow rates (maximum around 13 L/min). In this instance, the pump best efficiency point was likely closer to 13 L/min rather than 8 L/min. The average energy intensity of the assessed RHS was equal to 1.08 kWh/m^3 when taking into account a weighted average of the energy intensities of all rainwater-supplied end uses [123].

Also in Gold Coast city, Hood et al. [124] assessed the energy intensity of RHS at an ecovillage located in Currumbin Valley. The average energy consumption for the 700 W rainwater pumping systems installed in 24 households was 1.40 kWh/m^3 for direct feed supply from ground level rainwater tanks to consumption points. The energy intensity of the systems was calculated to be comparable to the local centralised town water system (1.20 kWh/m^3) [124]. Within the same region, Umapathi et al. [125] assessed the energy intensity of RHS located in 19 households in Pine Rivers, Caboolture, Redlands and Gold Coast. The rainwater distribution systems operated through direct feed with two types of town water back-up systems: trickle top-up systems and automatic switch devices. Trickle top-up systems were more energy intensive than automatic switches, at 1.59 and 1.46 kWh/m^3, respectively. It was found that this difference is attributable to town water pumping, as, in the trickle top-up systems, the back-up town water enters into the rainwater tank, and then is pumped by the distribution system. Therefore, the motor pump supplies both rainwater and back-up town water to end use points; whereas automatic switches bypass back-up town water from pumps, supplying rainwater only. The average energy intensity for all of the assessed systems was 1.52 kWh/m^3 [125].

Ferguson [126] conducted a detailed assessment of the energy consumption of RHS in Australia, which encompassed the assessment during one year of 52 houses in Sydney with rainwater supply to toilet cisterns, washing machines and external taps. All the studied houses were at most two years old with RHS, water efficient dual flush toilets (e.g. 3 and 4.5 L/flush), and water efficient washing machines (e.g. 60 to 80 L/cycle). The configuration of RHS varied as follows: the average catchment (roof) area was 210 m^2; 80% had first flush diverters of 10 L on average; all the rainwater tanks were at ground level with average capacity of 4.2 m^3; town water back-up systems were 90% automatic switches, 6% trickle top-up, and 4% none or others; in-line water filters were used in 46% of the cases; pumps were 35% external and 65% submersible; rainwater end uses included external uses at all times, toilet flushing at 92% of the time, and washing machines at 65% of the time. In general, the energy intensity increased with a decrease of average flow rates in the households. The analysis of single water consumption events showed that low flow rate (approximately 5 L/min) events in toilets and washing machines contribute the most to the total energy consumption in RHS, with an average energy intensity of 1.50 kWh/m^3. On the other hand, the energy intensity of events with high flow rates (> 15 L/min), which correspond to 2% of the total water consumption, were equal to 0.70 kWh/m^3 on average. The median and the average energy intensity of RHS was 1.48 and 2.08 kWh/m^3, respectively, varying from 0.76 kWh/m^3 to 10.80 kWh/m^3. Ferguson [126] suggests that this variation was mainly attributed to the performance of the pumping system, and hence that the correct selection of pumps should be considered as a critical component for the optimisation of the energy performance of RHS. By considering the median flow rate (6 L/min) applied to pump energy intensity curves derived from RHS with the lower, average and higher energy performance, energy intensity averages were calculated as 0.68, 1.51 and 2.4 kWh/m^3, respectively. The author argues that the energy performance of RHS can be improved through the adoption of pumps which operate efficiently under 10 L/min. Ferguson [126] also discussed the importance of RHS maintenance for an efficient energy performance, which includes leakage control and filter cartridge replacement. For instance, the lack of maintenance of an in-line filter installed after a pump in one of the studied RHS led to extreme energy intensity events (over 30 kWh/m^3) due to the clogging of the filter cartridge. The use of rainwater self-cleaning filters may appear as a solution to this issue as described by Vieira et al. [127].

Retamal et al. [17] also evaluated the energy efficiency of RHS installed at households in Sydney, Australia. In this research, several types of rainwater pumping systems were assessed, including 500 W to 890 W pumps, fixed and variable speed pumps, standard external, submersible and venturi pumps, automatic switch, trickle top-up, manual and no town water back-up system, and systems with and without pressure vessel. For standard external centrifugal pumps with town water automatic switch, Retamal et al. [17] found that the energy consumption in distribution systems for rainwater supply to toilets, washing machines, and irrigation taps varied between 0.90 and 2.30 kWh/m^3 (average 1.55 kWh/m^3). Retamal et al. [17] also studied the energy intensity of different designs for rainwater distribution systems for the supply of all household end uses. The energy intensities of RHS with trickle top-up combined with fixed speed pump and variable speed pumps with pressure vessel were 1.50 and 3.00 kWh/m^3, respectively [17]. In this study, the use of pressure vessels did not perform as expected with an increase of RHS energy intensity. In spite of its function of minimising the energy consumption by reducing the number of pump start-ups, the pressure vessel capacity needs to be equal to or greater than the total water demand for the supplied consumption point in

order to reduce pump start-ups and generate lower energy intensities [128].

In the study of Tjandraatmadja et al. [128], the energy intensity varied from 0.60 to 5.30 kWh/m^3 for single water consumption events to supply washing machines, dish washers, toilets, and taps. The authors assessed the energy intensity of three external fixed speed pumps with power rating of 200, 550 and 750 W. They experimentally determined that a lower pump motor power rating produced a lower energy intensity. It is likely that the two parameters that have most influenced the variations in energy intensity were the best efficiency point and the pump motor efficiency. The differences in the energy intensity of pumps decreased with an increase in the flow rate, which suggests that the selected pumps (RHS standard pumps in Australia) operate at their best efficiency point at high flow rates ($\geq$15 L/min) [128]. The energy intensity of two pumps from the same manufacturer presented similar results, despite their difference in power rating — 200 W and 500 W [128]. This could be due to the similarity in the motor and pump efficiencies of both the pumps. Therefore, the selection of rainwater pumps should be based on the pump efficiency and the matching between the best efficiency point and the most frequent flow rate operation. For example, a household that predominantly uses their rainwater for toilet flushing (i.e. low flow rate) will require a different pump than a household that irrigates their lawn extensively (i.e. high flow rate).

Beal et al. [129] evaluated the energy intensity of RHS at an eco-sensitive subdivision named Silva Park in Brisbane, Australia. In this study, the energy consumption of RHS with direct supply distribution system and ultraviolet (UV) disinfection system of five allotments, as well as the communal RHS, were monitored over 18 months. The allotment or household scale RHS were equipped with 630 W pumps and continuous operating 40 W UV lamps so as to supply potable and non-potable end uses. Disinfection is necessary only when rainwater is used to supply potable water end uses. The average energy intensity found for rainwater distribution systems was approximately 2.95 kWh/m^3, and ranged from 2.00 to 3.90 kWh/m^3 [129]. The elevated energy intensity of rainwater pumps were attributed to both high pumping heads and inefficient plumbing rainwater supply design, which often led to numerous start-ups of pumps. More specifically, it was found that between 45% and 60% of the energy required for pumping was consumed during start-ups [129]. When the energy from the UV disinfection systems was taken into account, the RHS energy intensity increased by about 73%, with an average of 5.10 kWh/m^3 and ranging from 4.60 to 5.70 kWh/m^3. This energy intensity range is higher than reverse osmosis desalination plants, currently reported at 3.75 kWh/m^3 in Australia [50]. Therefore, when rainwater is used to meet potable water demand and requires energy intensive UV disinfection systems, RHS need to be carefully designed in order to reduce the total energy intensity to supply rainwater.

In 2001, Brewer et al. [130] conducted a 1 year monitoring study of the operational performance of rainwater or greywater systems installed at seven sites in the UK. Among the studied sites, rainwater was used predominantly for toilet flushing; however, it was also used for drinking purposes in three sites, in which rainwater UV disinfection systems were used. Such sites presented a considerably high energy intensity, ranging from 5.60 to 7.10 kWh/m^3 [130].

Cohim et al. [131] evaluated the efficiency of RHS in low-income households in the metropolitan region of Salvador, North-eastern Brazil. Each system consisted of a 250 L header tank elevated at 1.9 m above floor level for the collection of rainwater from roof gutters. The system supplied laundry purposes by gravity, eliminating the need for pumping. The simplicity and energy neutrality of rainwater gravity systems make them attractive not only for low income areas in developing countries, but also in any building where energy efficiency objectives are set at utmost standards. In the UK, Parkes et al. [132] also describe the use of RHS with gravity distribution systems. Despite the benefits of such systems, the authors acknowledge that they typically have a small storage capacity and limited range of application for water supply in buildings in the UK.

Among the reviewed literature, there was an absence of empirical studies on the energy intensity of RHS in multi-storey buildings. As described by Parkes et al. [132], the use of RHS in multi-storey buildings is likely to have minor or no impacts on the total energy used at the building scale for water supply, as town water supply distribution also relies on on-site pumping in multi-storey buildings. The reviewed empirical studies revealed that the energy performance of RHS is intrinsically connected to the configuration of pumping, town water back-up and UV disinfection systems. Such studies have provided important clues to achieve high energy efficiency in RHS, including: (i) the use pumps with low pressure head to reduce the total energy embodied into rainwater [116]; (ii) the use of larger pipe diameters and low friction loss valves to reduce excessive head losses [116]; (iii) the selection of pumps with optimal flow rate similar to rainwater end use flow rates (i.e. usually under 10 L/min) [123,126,128]; (iv) the use of pumps with high motor (mechanical) and pump (electrical) efficiencies [128]; (v) the prevention or elimination of town water back-up systems with on-site pumping of mains water (e.g. trickle top-up systems) [125]; (vi) the prevention or maintenance of both leaks in order to avoid unnecessary pumping and energy consumption, and in-line filters after pumps to avoid clogging and excessive head losses [126]; (vii) careful selection of pressure vessels based on the water consumption volume per event in order to reduce pump start-ups and avoid an increase in energy intensity of RHS [17,128]; (viii) the prevention, adjustment or elimination of rainwater distribution systems with an elevated number of pump start-ups [129]; (ix) consideration of energy efficiency in the selection and design of UV disinfection systems for RHS with potable water requirements in order to avoid significantly high energy intensities [129,130]; and (x) the use of gravity systems with elevated tanks to collect and distribute rainwater to achieve neutral energy-intensity [131].

5.3. Energy intensity comparison

As described in the previous sections, on-site RHS are typically designed using simple concepts to supply non-potable water end uses (e.g. toilet flushing, laundry and irrigation), in which energy is required mainly for pumping. Where rainwater is used to supply potable water end uses (e.g. shower and internal taps), it usually undergoes treatment methods using energy consumption only for UV disinfection. On the other hand, centralised water supply systems require a higher level of complexity, necessitating energy for bulk water abstraction, raw water treatment and treated water distribution. In spite of the difference between the lower and higher levels of treatment typically required in RHS and centralised water supply systems, empirical studies show that the energy intensity of on-site RHS are usually larger than the average reported energy intensity of conventional centralised town water supply systems (Fig. 1).

The median energy intensity of the RHS described in the reviewed empirical studies (i.e. 1.40 kWh/m^3) tended to be 3 times higher than town water supply (i.e. 0.48 kWh/m^3), ranging from approximately 2 to 6 times from Australia to Taiwan, respectively. The greater energy performance of centralised systems is mainly related to the use of pumps with higher energy efficiency translating to higher economies of scale due to the higher water demands. As pointed out by Vieira [115], the usual low rainwater

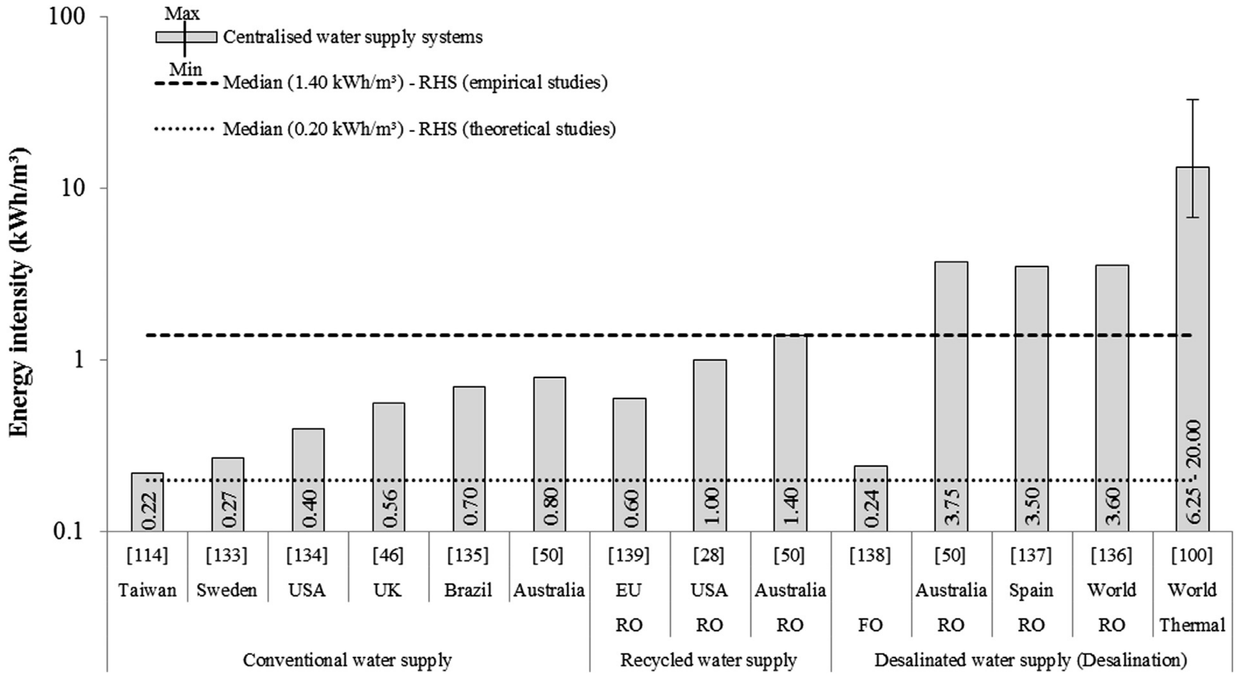

Fig. 1. Energy intensity comparison between centralised water supply systems and RHS [28,46,50,100,114,133–139]. *Note*: forward osmosis (FO) and reverse osmosis (RO).

consumption (< 600 L/day) is one of the limiting factors to achieve energy efficiency in RHS at single-family residential buildings.

Driven by water scarcity, a new era in the urban water management is commencing [53], in which conventional water supply systems are supplemented by alternative water sources. Therefore, the demand for alternative water sources is likely to increase, which will possibly enhance the energy performance of RHS, particularly in communal RHS with energy efficient rainwater distribution design. This scenario is favourable to expand the use of RHS, as the level of complexity of centralised water supply systems increase with the use of alternative water sources (i.e. salt water and treated sewage) which required a higher level of treatment, usually achieved by energy intensive technologies.

Alternative water supply technologies aimed at achieving water security objectives, without a considerable increase in energy demand, have been developing in the last decade. For example, obsolete desalination technologies based on thermal distillation has a minimum energy intensity of 6.50 kWh/m^3 worldwide [100]; while, in the present, the widespread use of reverse osmosis for desalination provides water at an average energy intensity of 3.60 kWh/m^3 worldwide [136], 3.50 kWh/m^3 in Spain [137], and 3.75 kWh/m^3 in Australia [50]. Moreover, promising technologies are expected to reduce the energy intensity of desalination processes to levels similar to conventional water treatment systems. It should also be noted that advanced forward osmosis desalination systems can achieve energy intensity values as low as 0.24 kWh/m^3 in certain cases [138]. Energy efficient reverse osmosis for recycled water systems have also been developed. For instance, studies have reported energy intensities for these systems of around 1.00 kWh/m^3 in California in the USA [28] and 1.40 kWh/m^3 in Australia [50]. In Europe, an energy intensity of 0.60 kWh/m^3 was achieved by using an optimised reverse osmosis system [139].

In this context of heightened focus on reducing the energy intensity of bulk water supply alternatives, the energy efficiency of RHS will also have to be improved from the current levels of energy intensity (e.g. median of 1.40 kWh/m^3). Likely, the development of energy efficient technologies and configurations for RHS will promote a reduction of the energy intensity of rainwater pumping systems to levels similar to theoretical studies (e.g. median of 0.20 kWh/m^3). Moreover, innovative concepts for RHS have the potential to neutralise their energy intensities. This will be probably achieved by systems that operate by gravity as described by Angrill et al. [101], Vieira et al. [127] and Parkes et al. [132]. A detailed discussion on how the energy performance of RHS can be optimised is provided in the following section.

6. Discussion

To date, RHS are typically not energy efficient, which may jeopardise their feasibility as an alternative water supply option [132,140]. This inefficiency is mainly attributed to rainwater distribution systems with inefficient and oversized pumps [118]. UV disinfection for potable rainwater supply may also cause a marked increase in the energy intensity of RHS [129]. In addition, the type of towns water back-up system also influences the energy intensity of RHS [17]. Therefore, new configurations and approaches for RHS are required [46,118], as energy consumption is a critical parameter for optimal water asset planning and management [53]. Table 5 presents a summary of positive and negative aspects related to the hydraulic and energetic performances of sub-systems in RHS. General impacts of RHS on surrounding areas are also discussed briefly.

The following sub-sections discuss in more detail the energy implications of RHS configurations, as well as future trends towards improving RHS design.

6.1. Rainwater consumption

The rainwater consumption, or user demand on the system, has a major influence on the energy intensity of RHS [140,141]. It can also influence the trade-offs between water and energy consumption for RHS, where the higher energy intensity of a RHS can be offset by water conservation strategies and vice versa [142]. Notwithstanding rainfall patterns, rainwater consumption is mainly influenced by demand (e.g. the type of connected

Table 5
Positive and negative aspects of rainwater harvesting sub-system.

Sub-system	Common practices	Type/ applicability	Positive aspects	Negative aspects	Energy consumption
Collection	Roof catchment	All types	Higher quality of raw rainwater in comparison to rainfall yields from other surface areas (e.g. storm water).	May present lower rainwater yields due to area constraints. May promote the contamination of rainwater with heavy metals, organic matter and/or pathogens depending on the roof type, surroundings and maintenance frequency.	No direct energy implications. Depending on the location and design of roofs, there may be opportunities to install rainwater gravity distribution systems without pumping requirements (i.e. direct supply from header tanks).
Treatment	First flush diversion	All types	Effective reduction of pollutant loads from collected raw rainwater.	Installation can be performed without considering the first flush volume of roof catchments. In regions with relatively low rainfall patterns, the diversion of the first flush may decrease significantly rainwater collection.	No direct energy implications. Its usage may indirectly reduce energy consumption by alleviating head losses of pressurised distribution systems with in-line filters after pumps.
	Gross filtration	All types	Removal of gross pollutants that may deteriorate the water quality in storage tanks.	May require continuous maintenance depending on the design.	No direct energy implications.
	Fine filtration	All types	Removal of fine particles that may be associated with pathogens. Improvement of rainwater's aesthetics.	May considerably increase the energy consumption of RHS when subsequent to pumps due to the accumulation of particles in the filter medium depending on the rainwater quality and maintenance frequency.	No direct energy implications. Its indirect energy implications will depend on its design and location. Filters which precede pumping will rarely require energy. Self-cleaning filters will usually prevent excessive particles and pressure losses.
	UV disinfection	Potable water supply	Use of rainwater for all water end uses. It is generally more effective in inactivating pathogens than chemical disinfection.	High energy consumption depending on the system design. Regrowth of pathogens due to lack of residual disinfectant.	UV disinfection may have high energy consumption, which can be somewhat managed if used with optimal design and only when potable water standards are required in order to avoid perverse energy outcomes.
	Chemical disinfection	Potable water supply	Use of rainwater for all water end uses.	May require continuous manual operation and by-products in the water. May also cause odour nuisance and intoxication.	May require energy if automatic dosing systems are used.
Storage	Large tanks	All types	Improvement of rainwater supply reliability. Indirect benefits include the possible reduction of floods in urban areas depending on the size and the density of rainwater tanks in a region.	Space constraints for above ground and underground tanks, and aesthetic issues for above ground tanks. The cost of large tanks may also be a limiting factor for the economic feasibility of RHS.	The static pressure head will vary with the location of storage tanks. The lower the static pressure from tank(s) to water end use points, the less energy is required to supply rainwater. Negative static pressure, when the tank is at a higher elevation than the consumption point, will generally allow gravity rainwater supply depending on the pressure requirements. The location of tanks will also influence the length of pipes and associated friction losses.
	Slim line tanks	All types	Improvement of rainwater supply reliability in space constrained sites.	Economical constraints.	As above
Distribution	Direct external supply	Fixed speed pump.	Low installation cost.	Require variable amounts of energy depending on end use flow rates.	Normally, the fixed speed pumps available on the market for RHS, usually within 200 to 890 W, operate efficiently at high flow rates (> 15 L/min.) and are suitable to supply external uses.
	Direct internal and external supply	Fixed speed pump	As above.	High energy consumption due to inefficient pump operation for some end uses.	Existing fixed speed pumps will fail to meet both high and low flow rate water demands at optimal energy performance. It will likely give rise to excessive energy consumption at low flow rates, as usually fixed speed pumps are selected/designed to meet the largest flow rate requirement.
		Variable speed pump	Enhancement of the energy performance of pressurised water supply with variable flow rate.	Economical constraints, and specialized installer required to adjust pumping system to the most used flow rates.	Energy benefits may arise from the use of variable speed pumps which can achieve optimal energy efficiencies at both low and high flow rates. Nonetheless, it still requires careful selection to meet site specific conditions and intended outcomes.
		Pressure vessel	Enhancement of the energy performance of pressurised water supply with variable flow rate.	Economical constraints, and specialized installer required to adjust vessel capacity to most used volumes per consumption event.	Allows the reduction of pump start-ups by accumulating pressure into a vessel that boosts rainwater to consumption points. Its energy performance is a function of its capacity to supply

Table 5 (*continued*)

Sub-system	Common practices	Type/ applicability	Positive aspects	Negative aspects	Energy consumption
					multiple rainwater consumption events without constant pumping.
	Header tank	Indirect supply	Very low energy consumption, pump operation at the best efficiency point, rainwater supply during power outages.	Limited compliance with some pressure requirements. Installation may be limited by space or structural constraints depending on the size of the header tank.	Generally, indirect supply systems with header tanks will enable the reduction of pump start-ups and operation of pumps at the best efficiency point. The pipe diameter between the ground level tanks and the header tank can be also optimised to promote minimal head losses and high energy efficiency.
		Direct supply	No energy consumption.	Reduced rainwater supply capacity, and limited compliance with some pressure requirements.	The rainwater supply can be performed entirely by gravity. By using such system, energy neutrality for operation can be achieved in RHS.
Town water back-up	Trickle top-up	All types	Simple installation in which town water is supplied into rainwater tanks when rainwater is not available.	May mislead RHS owners about the availability of rainwater.	May increase pumping operation in RHS with direct supply from storage tanks as town water may be pumped on-site along with rainwater. In multi-storey buildings, it may have neutral energy implications as town water is usually pumped on-site at all times in this building type depending on the pressure requirements.
	Automatic switch	All types	Avoid pumping of town water in direct pumped systems.	Require more components, and less financially economical. May mislead RHS owners about the availability of rainwater.	This system will require energy to power controllers and valves.
	Manual	All types	No energy consumption.	May not be practical. Potential unavailability of water due to operational lapses.	Neutral energy demand. For RHS with high supply:demand ratio, manual systems may require minimal operation and promote energy savings as standby energy consumption may be significant in RHS with low rainwater demand (<600 L/day).

appliance/fixture and demand on those appliances/fixtures), rainwater storage tank size, and catchment area size [91,143].

Low rainwater consumption patterns can lead to high energyintensities in RHS. This is because RHS also consume energy for purposes which are independent or not totally related to rainwater consumption, such as: standby mode, pump start-ups and disinfection [17,119]. For instance, as described by Vieira [115], the energy consumption of pumps in standby mode is independent from rainwater demand, and as such, the less rainwater consumed, then the higher the energy intensity associated with standby mode. Additionally, pump start-ups draw the same amount of energy for pumping events despite the duration or the total rainwater consumption; hence, the shorter the pumping event, the higher the energy intensity associated with pumpstarts [128].

Even using cutting edge technologies with high energy efficiency, buildings with low rainwater consumption patterns will be likely to have poor RHS energy efficiency. The installation of RHS in such buildings requires careful consideration, as it may be only feasible when using direct gravity supply with header tanks in energy neutral RHS. Possibly, higher rainwater consumption patterns in multi-storey buildings may reduce the energy intensity of RHS, and hence result in a lower overall energy intensity compared with single-storey buildings.

6.2. *Fit for purpose end uses*

The end uses that are supplied by rainwater also have a relevant impact on the energy implications of RHS. This relates chiefly to the required treatment level of rainwater for each end use. For instance, when potable water end uses are supplied by rainwater, disinfection is required to inactivation pathogens [132,144], unlike non-potable end uses, which often do not require disinfection [120].

UV disinfection is becoming an increasingly popular method for microorganism inactivation in RHS [144]. The main advantages of UV disinfection are: no handling and storing of chemical products, high disinfection efficiency (e.g. compared with chlorination), minimum maintenance, and minimum health risks [145,146]. However, UV disinfection requires energy, and, depending on the UV system configuration, the disinfection cycle will be a key driver of the total energy consumption in RHS.

Beal et al. [129] found that continuously operated 40 W UV disinfection systems had an average energy intensity of 2.15 kWh/m^3. Such a high energy intensity was believed to be associated with the excessive UV dose and the large volume of treated rainwater. UV doses in excess of the required disinfection amount will not adversely affect the water quality like chemical disinfection (e.g. over-chlorination may cause intoxication); although, it will be associated with unnecessary use of energy. Therefore, UV systems have to be designed to deliver the required dose for disinfection, which depends on the UV radiance absorbance of the water, the raw rainwater quality, and the required end use water quality level [115].

There are four key parameters in the optimisation of UV disinfection systems [115]: (i) conversion efficiency of electricity into UV radiation; (ii) number of start-ups (as most UV lamps are fluorescent, and hence require warm-up before reaching the maximum UV production); (iii) standby energy usage; and (iv) rainwater demand, which will influence the number of cycles a discrete volume of rainwater is exposed to UV radiation to deactivate pathogens.

Another parameter that influence the energy intensity of UV disinfection is the ratio between the volume of water consumed and the volume of water treated. After 6 h, UV treated water may undergo a re-growth of microorganisms [147], thus requiring a new cycle of treatment. UV systems can be optimised by only treating the required volume that will be used. This can be achieved by using on demand operation, which can promote a considerable reduction of UV disinfection requirements in RHS [148].

Vieira [115] has theoretically optimised UV disinfection reactors for rainwater treatment by assuming one disinfection cycle each 6 h for the daily rainwater demand reserved in a header tank. The results indicated that UV disinfection energy intensity varied from 0.09 to 0.19 kWh/m^3 for a 200 L/day rainwater demand without considering the energy for standby mode or parasitic losses [115]. Considering such additional energy requirements equal to 2 and 4 W, the energy intensity of the UV disinfection system would increase by up to 0.24 and 0.48 kWh/m^3, respectively [115].

6.3. Supplied consumption points

The energy feasibility of RHS is dependent on the energy intensity of other water sources that can be used to supply similar consumption points to rainwater. Generally, RHS are compared against centralised town water reticulation systems, which have widespread use worldwide.

Normally, the design of town water distribution systems allow for the supply of single and double storey buildings with minimum required pressures for fixtures and appliances. Nevertheless, in multi-storey buildings, town water pressure is not always sufficient to supply all consumption points for all of the building storeys. Such buildings use pumps to re-pressurise town water to header tanks or direct supply consumption points [33]. As a result, the use of RHS in multi-storey buildings have minor implications on the total energy used for water services as town water pumping is also required on a building scale [132]. Thus, for this building type, RHS may promote a reduction of the energy intensity of water services.

However, it is important to notice that, in multi-storey buildings, there is also a proportion of potable water directly supplied by town water systems to consumption points at lower floor levels. Thereby, energy assessments of RHS in multi-storey buildings need to consider the fraction of the total rainwater consumption which can also be supplied by town water without pumping [132].

6.4. Direct supply system

Direct supply systems distribute rainwater straight from the rainwater storage tank to end use points. Pumping may or may not be required, depending on the location of the rainwater storage. Typically, the storage tank is at ground or underground level [10,132], and then rainwater distribution is usually performed by fixed speed pumps [17]; although, header tanks directly connected to rainwater collection and treatment systems can also perform direct supply without requiring pumping [131,132].

6.4.1. Fixed speed pumps

Direct supply systems fitted with fixed speed pumps are widely used in Australia and UK [17,128]. The energy demand for such a distribution system is highly dependent on the pump power rating [116]. This parameter is determined by considering both the peak water flow rate and the maximum hydraulic head of pumps. Usually, among different end uses supplied by one direct fixed speed pump, the end uses with low and high flow rates will present high and low energy intensities, respectively. This is mainly attributed to the fact that pumping systems are usually designed to supply peak demand [123], and hence will generally have their best efficiency point at high flow rates.

The energy performance of direct feed RHS can be improved by designing systems in which both the rainwater demand and end use flow rates are taken into account. The first parameter will be used to determine the end use with the largest rainwater demand, whereas the second, the most prevalent flow rate required at end use points. Then, rainwater pumps should be selected to have their best efficiency point at the most prevalent flow rate in the RHS. For instance, irrigation and washing machines alike tend to present an elevated water demand and higher flow rates compared to other household water uses (e.g. toilets and internal taps) [69]. In this instance, the supply of rainwater either to irrigation and washing machines or toilets and internal taps by the same pumping system may be more energy efficient than systems which supply end uses with different flow rates. By optimising the operation of pumps in direct supply pumped RHS, it is possible to supply rainwater at similar or lower energy intensities than other alternative water supply systems (e.g. recycled water and desalination), i.e. under 1.5 kWh/m^3 [128].

6.4.2. Variable speed pumps and pressure vessels

Systems which use more sophisticated technologies, including the use of variable speed pumps and pressure vessels, may promote a reduction in the energy intensity of direct feed rainwater distribution systems.

For systems fitted with variable speed pumps, it is important to match the pumping best performance flow rate range to the end uses flow rate and pressure requirements [17]; whereas, for pressure vessels, their water volume capacity has to be greater than the end use rainwater demand [128]. Therefore, the energy efficiency of both systems will be highly dependent on the configuration and calibration of such systems [17].

The design and calibration of distribution systems fitted with either variable speed pumps or pressure vessels is performed by determining the water consumption pattern. Such information is not available for newly constructed developments, and rarely is it available for existing buildings as the required water monitoring equipment and analysis is a financial and resource intensive exercise. Moreover, the use of variable speed pumps and pressure vessels can require considerable implementation costs for RHS. Therefore, to date pressure vessels and variable speed pumps in direct feed RHS are likely to be unfeasible until further development of these systems both towards energy efficiency and cost-effectiveness is undertaken.

6.5. Indirect supply systems

Indirect supply systems involve pumping rainwater from a rainwater storage tank to a header tank, and then distributing rainwater from the header tank to end use points by gravity. The use of header tanks can significantly mitigate the energetic impacts of RHS which are fitted with storage tanks at ground or underground levels [101].

Using indirect distribution systems, the daily rainwater demand is typically pumped to the header tank at an optimal flow rate. Thus, in contrast to direct feed supply systems, indirect supply systems both facilitate the optimisation of pump operation, and also reduce pumping demand for rainwater distribution [46]. For instance, in directly pumped supply systems, the selection and calibration of pumps are constrained by the variable flow rates at consumption points in accordance to the water usage pattern [128]. In indirect supply systems, the ideal flow rate and pressure

can be determined during the design phase; considering both the head pressure and the flow rate required to transfer water from lower rainwater tanks to header tanks.

On the other hand, pressure requirements can make the use of header tanks inappropriate as the rainwater distribution systems will operate at low pressures depending on the location of the header tank and distribution pipes length and diameter. However, high pressure distribution systems are not required at all supply points. Therefore, in order to enable a more optimised use of header tanks in RHS, a reduction of the pressure requirements by guidelines can be adopted. For instance, in Brazil, most of the households use indirect town water supply with the use of header tanks due to the intermittent town water supply. Consequently, the Brazilian guideline for plumbing systems – NBR 5626 [149] – states that the minimum piping diameter is 20 mm, and minimum pressure requirements for water fixtures and appliances in buildings is 10 kPa, with the exception of toilet cisterns and toilet flush valves, which are 5 and 15 kPa, respectively. Similar values of pressure were described for RHS with indirect supply in the UK [150]. In Australia, the amendment of minimal piping diameter for internally plumbed RHS from 12 to 20 mm is also discussed [148].

In countries with direct town water supply to end uses in buildings, the minimum pressure requirements for water fixtures and appliances are higher than 10 kPa. For instance, in Australia, the minimum pressure required for washing machines vary between 40 and 100 kPa, 30 and 150 kPa for dishwashers, and 150 kPa for toilet cisterns [128]. In order to achieve higher pressure requirements, header tank distribution systems may be assisted by pump boosters. Even with the use of pump boosters, header tanks will still have lower energy intensities than direct feed pumping systems as the positive pressure from header tanks will allow the selection of low power rating pumps and assist in pump start-ups.

6.6. Pump efficiency

The motor and pump efficiency of rainwater distribution systems are also an important parameter to enhance the energy efficiency of RHS, as it directly influences their energy intensity [119]. Despite the similarity between the RHS concept presented by Ghisi and Oliveira [117] and Chiu et al. [113] (i.e. use of header tank with daily rainwater pumping in single-storey buildings), the energy intensity calculated in the former study was 3 fold greater than the one calculated in the latter study. This difference can be related to the energy efficiency assumed for pumps; Chiu et al. [113] and Ghisi and Oliveira [117] considered pump efficiencies equal to 65% and 37%, respectively.

Retamal et al. [17] reported that small pumps have low energy efficiency, resulting in a global efficiency (i.e. combined motor and pump efficiency) of approximately 35%. Historically, RHS usually required the use of small pumps, resulting in a concomitant reduction in overall energy efficiency. However, an increase of pump size in RHS may also prove to be inefficient, where water end uses flow rates in residential buildings are low. Moreover, despite the higher energy efficiency of larger pumps, they typically demand more energy for start-ups and standby [115]. As a result, their use in RHS can increase the energy intensity for standby and start-ups as well as during active pumping.

RHS energy efficiency can be enhanced by selecting pumps which match their best efficiency point to the flow rate and pressure requirements of water end use points. This may not be practical for systems with direct supply using fixed speed pumps due to the possible diversity of flow rates for different end uses. On the other hand, for header tank distribution systems, constant flow rate and pressure operation is achievable, and thus allowing a better match of the best efficiency point and operation flow rates.

6.7. Pump start-up and standby mode

The energy requirement for pump start-up and standby mode are almost independent of the total rainwater consumption. Therefore, pumps have to operate with minimum energy consumption for both energy uses. Typically, the lower the rainwater demand, the higher the energy intensities associated with pump start-up and standby mode [115]. The number of start-ups will depend directly on the rainwater consumption pattern as well as on the system configuration. For direct supply systems with fixed speed pumps, there will be one start-up for each water use event [128]. For indirect supply systems, the pump start-up frequency will be determined by the capacity of the header tank and the rainwater consumption pattern [119]. Therefore, with the use of header tanks, the number of start-ups can be considerably reduced.

Standby energy consumption in energy efficient systems is usually low – approximately 0.002 kWh [17]. However, a considerable percentage of the total energy intensity of RHS can be derived from standby energy consumption in systems with low rainwater demand [115]. The standby energy can be either reduced by selecting energy efficient controllers, or eliminated by installing manual pump switches.

6.8. Town water back-up system

There are two commonly employed methods for supplementing rainwater supply with town water when rainwater supply cannot meet the rainwater demand: trickle top-up systems and automatic switches [14]. The former can operate both mechanically or electronically, whereas the latter works only electronically through the use of level sensors and solenoid valves.

Trickle top-up systems tend to be more energy intensive in directly pumped supply systems, as the back-up water is supplied to the rainwater tank [125]. Therefore, both rainwater and back-up town water are pumped in this system. However, when mechanical trickle top-up valves are used to supply back-up water to header tanks, no energy is required for back-up water supply.

Automatic switch systems are continuously energised in order to maintain constant operation of controllers and valves. Such systems supply back-up town water directly to end use points [125]. Consequently, they generally present a lower energy intensity than trickle top-up systems in direct pumped supply RHS [125].

Manually operated systems also appear as a solution to avoid energy consumption of a town water back-up system. Nonetheless, systems will be more prone to operational lapses and associated water deficiencies when rainwater is not available. Yet, in RHS with considerably higher yields and storage capacity in relation to consumption, town water supply may be required at a low frequency. Therefore, under such conditions, manual town water back-up systems may promote energy savings without negative operational implications.

6.9. Towards energy efficient rainwater harvesting systems

The enhancement of the energy performance of RHS will likely allow an increase of positive trade-offs between water and energy services at a building scale, which may also improve the performance of the water and energy sectors in the future as energy efficient alternative water sources are crucial for the development of water and energy resilient cities. Therefore, RHS are a key component of the urban water-energy nexus.

Through targeted design aimed at addressing the energy intensity of RHS, innovative energy efficient pumping and UV systems can be developed. In order to optimise the energy

performance of pumping and UV systems for RHS, four parameters ought to be considered: (i) energy efficiency (pump efficiency and UV conversion efficiency, respectively); (ii) number of start-ups; (iii) standby energy usage; and (iv) rainwater consumption patterns. The type of town water back-up system is also important; in direct pumped distribution systems, automatic switches are more energy efficient; on the other hand, in indirect supply systems, trickle top-up can supply town water to header tanks without energy implications.

The most prominent solution for enhancing the energy efficiency of rainwater distribution systems is the use of header tanks, as this configuration both reduces the number of pump start-ups and allows the pump to operate at the best efficiency point. However, the optimised use of header tanks will be only achieved through a reduction in pressure requirement at end use points to a minimum pressure of approximately 10 kPa (i.e. value based on the plumbing code of Brazil). A reduction in pressure requirement can also be favourable to enhance the energy performance of RHS with direct supply from ground level tanks to end use points through the adoption of low pressure pumps [116]. Moreover, this reduction may have the potential to reduce the energy intensity of water services as a whole, as the higher the pressure requirements at end use points, the higher the energy intensity of the water distribution systems [2]. In addition to header tanks, UV disinfection systems with on demand operation can promote a reduction of the energy intensity of RHS when potable water standards are required [148].

If limitations regarding the energy intensity of RHS during operational phase can be overcome, RHS will likely promote greater environmental benefits on an urban scale. Nevertheless, the supply capacity – quantity and quality – of rainwater will depend on local atmospheric air quality, rainwater harvesting design, rainwater demand and rainfall patterns. Furthermore, to date the capital costs of alternative water supply strategies are similar to conventional water supply, and hence they will be only used either for water security enhancement or for environmental protection [33,140].

Overall, the potential perverse energy outcomes from policies that mandate the universal use of RHS in the name of environmental sustainability may be avoided through effective guidelines addressing the energy efficiency of RHS. Despite the reduced energy performance of RHS in relation to centralised systems, they are commonly known as “eco-friendly” without taking into account life cycle energy impacts of such systems during components production, installation, operation, maintenance, and decommissioning. Therefore, it is recommended that energy efficiency considerations are embedded into management policies covering the installation, operation and maintenance of RHS. However, the importance of water and energy is generally considered only during scarcity periods [151], without the anticipation of issues related to the water-energy nexus.

7. Conclusion

The median energy intensity of the entire sample of reviewed theoretical and empirical RHS studies was 0.20 and 1.40 kWh/m^3, respectively. Empirical studies provide strong evidence that currently implemented RHS often have operational energy intensities that are far higher than centralised town water systems and are similar to recycled water supply systems. On the other hand, as outlined in theoretical studies, emerging configurations for RHS based on gravity rainwater supply with the use of header tanks have the potential to provide fit-for-purpose supply at energy intensity levels much closer to conventional town water supply systems.

A carefully considered RHS configuration is paramount to ensure lower environmental impacts when using rainwater in buildings. Depending on the local characteristics (e.g. rainwater demand, building type (single-storey or multi-storey), RHS subsystems design, potable water plumbing system design, town water energy intensity, etc.), RHS may promote environmental and economic benefits or drawbacks. For instance, RHS with direct pumped rainwater supply may increase the energy embodied into the water consumed at single-storey buildings, whereas it may promote energy savings in neighbouring multi-storey buildings due to on-site town water pumping requirements. Thus, it should not always be assumed that the installation of RHS to achieve water security imperatives has an overall positive effect on the environment, as it may have perverse energy outcomes; nor that the energy performance of RHS is always inefficient, as it may vary significantly depending on site specific and regional conditions.

In this context, the improvement of studies in this area for different buildings types and in different regions of the world will play a major role for the development of energy efficient RHS. Further investigation and synthesis of the water-energy nexus implications of RHS, as well as the entire spectrum of alternative water and wastewater supply systems, will enhance urban water planning and decision making.

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